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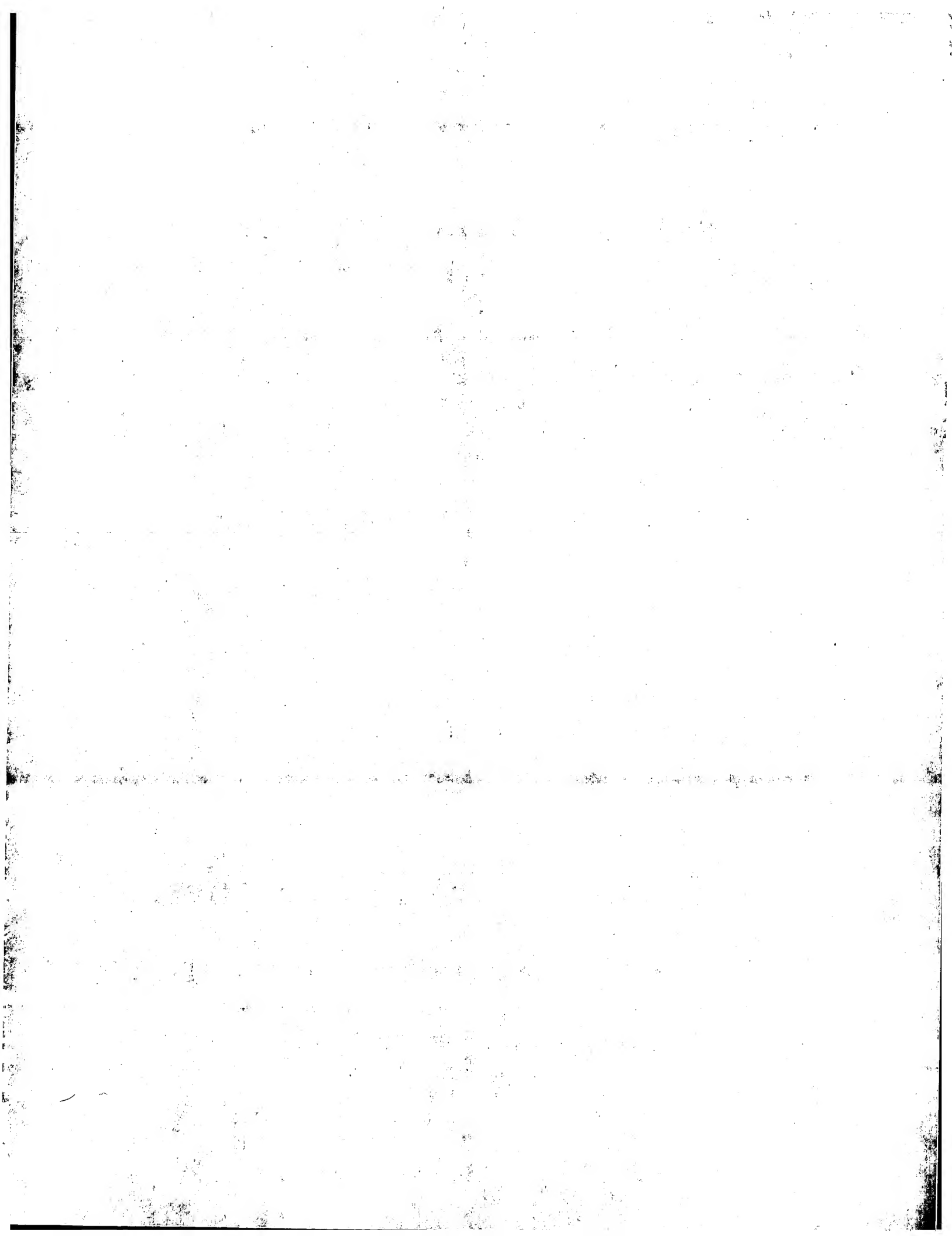
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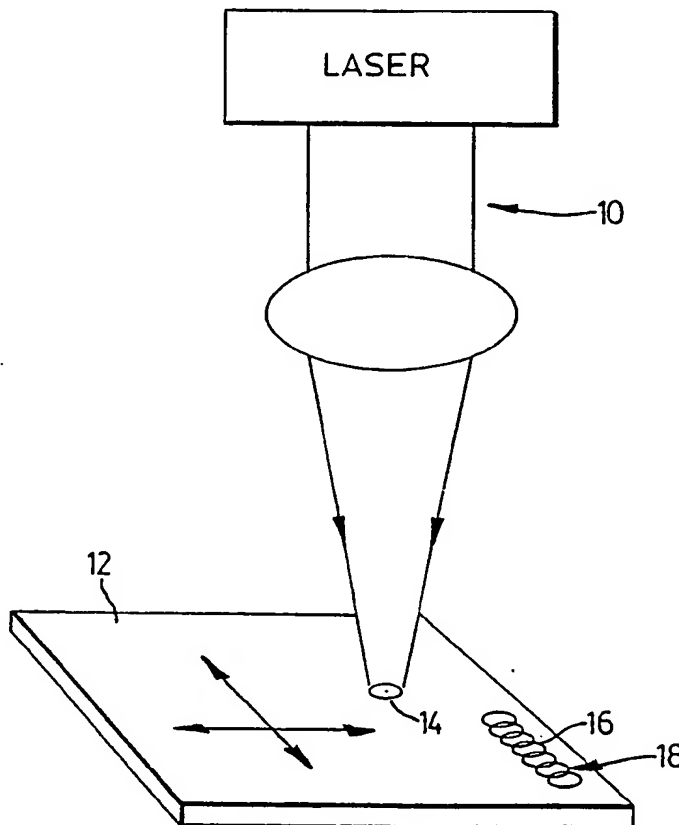


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(54) Title: LASER SURFACE TREATMENT**(57) Abstract**

A method of modifying the reflectivity and emissivity of a surface of a material comprises the steps of irradiating the surface with a beam of coherent pulsed radiation at a power sufficient to generate a surface plasma and scanning said beam across said surface. Successive pulses of radiation are caused to overlap and chemical change at the surface is promoted by provision of a localized atmosphere. The surface produced has features on a scale of less than 50 microns and is restricted to a depth of less than 10^{-3} cm. The body of the material is not affected.



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LASER SURFACE TREATMENT

The present invention relates to a method of modifying the reflectivity and/or of a surface of a metal.

5

Most surfaces reflect radiation over a wide range of wavelengths and do so with a varying reflectivity at different wavelengths. This characteristic can be used in a number of ways and has differing effects. For example, in an armaments environment, a laser is used to interrogate a vehicle and the signature of the vehicle is determined by the reflectivity of the surface. This is used to identify an enemy and the type of vehicle. The emissivity of a surface, which is related physically to the surface reflectivity is also an important parameter in determining the rate with which a surface loses or gains heat by radiation. The emissivity of a surface is for example critical in the cooling of spacecraft where maximum emissivity is desirable to reduce the temperature of the spacecraft and avoid damage to the vehicle. Such surfaces would have a low reflectivity at wavelengths in the infrared.

25

The emissivity of a surface can be modified in a number of ways. To enhance cooling of a surface in a spacecraft it is known to use special paints but these are prone to erosion due to the radiation, atoms and ions present in space. Similarly, specific materials or paints have been used on armaments to change their reflective characteristics and reduce their reflectivity to radar and laser range-finding devices. However, these treatments tend to be expensive and not permanent.

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It is, therefore, an object of the present invention to provide a method of modifying the reflectivity and hence the emissivity of a surface that obviates or mitigates the above disadvantages.

According therefore to the present invention there is provided a method of modifying the reflectivity of a surface of a material comprising the steps of irradiating the surface with coherent pulsed radiation at a power sufficient to generate a surface plasma and scanning said radiation across said surface.

In general terms the present invention modifies the reflectivity of a surface by generating a surface plasma which, combined with the pulsed nature of the radiation, produces fine surface irregularities and leads to a change, typically a reduction, in the reflectivity of the surface. A chemical change is also enhanced with the surface plasma that is generated. This chemical change at the surface can be promoted by providing a localized atmosphere of a specific gas, for example oxygen to promote oxidation of the surface. This processing also has the effect of modifying the thermal emissivity of these surfaces.

It has also been found that the surface produced leads to a significant increase in the convection losses thereby improving the heat transfer characteristics of the material.

Embodiments of the invention will now be described by way of example only with reference to the accompanying drawings in which Figure 1 is a perspective representation of a laser surface treatment technique;

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Figure 2 is a graph illustrating the reflective characteristics of the surface of one type of material;

Figure 3 is a graph illustrating the wavelength dependence of the reflectivity of the surface represented in Figure 2 after the laser treatment technique of Figure 1;

Figure 4 is a graph illustrating the reflective characteristics of a surface of a second material (aluminum);

Figure 5 is a graph illustrating the reflective characteristics of the surface represented in Figure 4 following the laser treatment technique represented in Figure 1;

Figure 6 is a graph illustrating the effect on the reflective characteristics of an aluminum surface caused by varying the periods of treatment by the technique represented in Figure 1;

Figure 7 is a curve similar to Figure 6 showing the relationship between emissivity efficiency and the number of pulses of laser radiation where the pulses partially overlap.

Figure 8 is a curve similar to Figure 7 showing relationship between emissivity efficiency and number of pulses for a stationary sample of material.

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Figure 9 is a curve showing the effect of different energies of the incident beam on the absorptivity of an aluminum surface.

5 Figure 10 is a curve showing the effect of varying amounts of the treatment of Figure 1 on the convective loss of the material used in Figures 6 to 9.

10 Figure 11 is a graph similar to Figure 6 showing the effect of the treatment on copper;

15 Figures 12 to 22 are reproductions and electron microscope scans of samples described in chart 1 below.

Figure 23 is a schematic representation of an alternative apparatus to that shown in Figure 1;

20 Figure 24 is a representation of a material having selected areas of its surface treated by the technique of Figure 1.

25 Referring therefore to the drawings, in Figure 1 there is shown a laser 10 irradiating a surface 12 of a material. The laser is finely focused to a point 14 typically having a surface area in the order of 1 mm². The material 12 can be moved relative to the laser 10 about two mutually perpendicular axes so that the laser can be moved to any point on the surface 12.

30 The laser 10 is operated to produce pulsed radiation and focused to the point 14 so that the intensity of the beam is sufficient to generate a laser supported detonation wave. Typically, the threshold for

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plasma ignition leading to a detonation wave is about 5×10^8 watts/cm², i.e. a fluence in the order of 20J/cm².

5 In use, the laser 20 produces pulsed radiation
and the material within the spot 14 irradiated at a
sufficient intensity so as to form a surface plasma.
Focussing of this radiation to produce an intensity
10 exceeding the threshold for plasma production results in
an evaporation and melting of surface material.
Material removed forms a vapor over the surface that is
heated by the laser beam to form a plasma. The shock
wave associated with this plasma impacts onto the heated
surface and produces a surface roughening as liquid
15 material is ejected away from the focal spot. It is
this surface roughening together with oxidation of the
hot material that produces a change in the reflectivity
and emissivity of the material. As the laser 10 is
operated, the spot 14 is scanned across the surface 12
20 by movement about one of the axes. After completion of
a row along one axis, the material is moved along the
other axis and the scan repeated. This continues until
the whole surface has been treated and a roughening of
the entire surface has been effected.
25 Hence an extended bulk area is built up by successive
scans.

30 The preferred apparatus is an Excimer laser,
operating at a wavelength of 308 nm and providing an
energy per pulse of between 10 and 1000 mJ and a pulse
width of less than 100 ns, typically in the order of 30
ns. This is operated at a repetition rate of 50 Hz with
scan speed across the surface of 7 in/min. Typically,
each area on the treated surface will be irradiated by a

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plurality of pulses, preferably more than 5 and more preferably more than 7. In the example noted above, the number of pulses is 17. The effect of irradiating the surface as noted above is to provide a number of overlapping pits indicated at 16 arranged in lines indicated at 18 across the surface. As will be described in further detail below, the surfaces produced exhibit a characteristic roughness with gross features produced by the overlapping pulses and, within the gross features, a small scale structure with a scale of less than 50 microns.

The change of reflectivity as a result of this treatment particularized above on the surface of stainless steel may be seen with reference to Figures 2 and 3. Figure 2 shows a plot of reflectivity versus wave number ($1/\text{cm}$) for untreated material. It will be seen that the reflectivity varies between 67% and 80%, between 4000 and 400 wavenumbers with characteristic peaks exhibited at particular wavenumbers.

As seen from Figure 3, after being treated in a manner described above, the reflectivity has been reduced to a range of 18 - 69%, between the same wavenumber limits with the peaks significantly diminished.

Figures 4 and 5 show the effect of the treatment on aluminum. In figure 4 it can be seen that the reflectivity for untreated material varies between 47 and 57% between 4000 and 400 wavenumbers. After treatment as shown in Figure 5, the reflectivity has been reduced over the entire range between 4000 and 400

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wavenumbers. Of particular importance in the curve shown in Figure 5 is the dramatic reduction in reflectivity at 3600 wavenumbers and at 800 wavenumbers. The decrease at 3600 cm^{-1} may be attributed to the formation of surface hydroxide during treatment. Similarly, the formation of a surface oxide causes a corresponding reduction in the reflectivity of the treated sample at 800 wavenumbers.

It will be apparent, therefore, that the surface treatment can be enhanced by providing a localized atmosphere, such as an oxygen-rich atmosphere, at the focal point of the laser beam during irradiation. This would promote the formation of oxides and reduce the reflectivity further. Similarly, it may be preferred to utilize nitrogen-rich atmospheres to generate nitrides at the surface if they show a significant reduction in surface reflectivity at useful wavelengths.

The effect of the number of overlapping pulses is best illustrated in Figure 6. This curve shows the reflectivity at a fixed wavelength, typically that used by a laser radar, i.e. 10.6 micron versus the number of overlapping laser pulses for aluminum treated with a pulsed excimer laser operating under the conditions noted above an energy of 160 mJ/pulse.. It will be seen that as the number of pulses increases, i.e. the scanning speed is reduced or the pulse repetition rate increased, the reflectivity of the surface to radiation at a wavelength of 10.6 micron is progressively decreased, i.e. the emissivity at 10.6 micron is progressively increased. Once the material has been subjected to a certain number of pulses, in this case 60

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or so, there is tendency for the curve to become non-linear, indicating that minimum reflectivity has been attained. The number of pulses required to attain minimum reflectivity will of course vary from material to material and with the wavelength used to interrogate the surface. In each case however a significant effect is obtained after several pulses, more particularly 5 pulses and more particularly after 70 to 100 pulses.

This effect is attributable to the surface roughening and to the chemical change that occurs at the surface. As noted on Figure 6, as the number of pulses increase, the oxide creating process is enhanced which contributes to the decrease in reflectivity until such time as saturation of the surface with oxide occurs at between 60 and 70 pulses. As can be seen from Figure 7 a corresponding increase in the emissivity of the surface is obtained. The curve of Figure 7 plots the emissivity efficiency expressed as a percentage of black body radiation against the number of pulses to which the surface is subjected. It will be observed that a rapid increase in emissivity occurs after several pulses with a progressive levelling off after 20 to 30 pulses.

Figure 8 shows similar results where successive pulses are coincident, i.e. the laser and material are relatively fixed and shows that whilst a similar effect is obtained its magnitude is approximately 50% of that produced with partially overlapping pulses. Accordingly it is believed that relative movement between the laser and the material surface is beneficial for producing the optimum surface effect as well as facilitating processing.

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5 The effect of intensity of the incident beam is illustrated in Figure 9. It will be noted that with higher energy levels, the initial change in reflectivity is increased but rapidly reaches a limit. The lower energy level also shows a dramatic increase but continues to increase the absorptivity (i.e. reduce the reflectivity over a greater number of pulses). This effect may be attributed the material removal that occurs at higher energy levels that inhibits the formation or deposition of oxides. In this plot the absorbivity to radiation emitted from a CO₂ laser is plotted.

10 A further beneficial effect is illustrated in Figure 10 where the effect of the resultant surface on the convective loss is shown. It will be seen that after relatively few pulses a significant increase in convective loss occurs, in the order of 300% to 400%. Thereafter the convective loss is relatively constant.

15 It may be surmised therefore that the initial exposure of the surface produces a surface roughening that increases surface area and reduces reflectivity. Progressively increasing numbers of pulses maintain the increased surface area but also promote formation of chemical compounds, particularly oxides that contribute to the further reduction in reflectivity.

20 As may be seen in Figure 11, a similar effect is obtained with copper as with aluminum with a significant change in reflectivity occurring after 5 pulses, more significantly after 10 or more pulses.

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The parameters effecting surface treatment are illustrated in Table 1 below where tests produced under a variety of conditions are summarized.

- 10-A -

TABLE I

Excimer (303 n.M.) Laser Parameters		Material	S.E.M. Fig.	Surface Characterization	Absorptivity
Fluence 44 J/cm ² 95 J/cm ²	Over- lapping pulses	A1	11	surface roughness only 5-20 microns	.08 (8%)
	50	Type 1100	12	underlying surface features covered with oxidized mat.	.25 (25%)
	500	500 microns thickness	13	new structure in oxidi- zed material 10 microns.	.95 (95%)
	35		14	fine structure, .5 - 20 microns within coarser structures. Shows begin- nings of oxide growth.	.3 (30%)
	50		14	continued oxide growth, the filling up of the line structure.	.38 (38%)
35 J/cm ² 26 J/cm ² 26 J/cm ² 65 J/cm ²	36	Cu 126 micron thickness	15	Top view showing edge of processed track & surrounding region.	.4 (40%)
			17	side view of processed track, 2-5 micron structure.	
			18	top view showing structure within processed region.	
	150 stationary pulses		18	cross-section shows that 150 pulses has removed Cu to a depth of 100 microns, with no modification to the underlying bulk material.	
	750 stationary pulses		20	shows redeposited oxidize droplets outside of irradiated region. Particle size 1-6 microns. Foreground shows untreated smooth Cu surface exposed in the cross-section.	
	930 stationary pulses	A1	21	shows recrystallized structure within irradiated region. Asperity structure 18 microns. Central depressed shows deformation due shock wave associated with such pulse.	

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5 The surfaces showing reduced reflectivity and increased emissivity each have a roughness with small scale structures with a scale of less than 50 microns and it will be observed that as the number of pulses increases, oxides are formed further contributing to the reduction in reflectivity.

10 At the high incident intensities used in the present invention, the primary effect appears to be the production of a surface plasma. This plasma is created when vapourized target material is heated by incident radiation via inverse bremsstrahlung. This appears to be followed by the formation of a laser supported absorption wave that further couples laser energy into the target, increasing the material removal rate. Under these conditions, liquid is expelled from the focus by the shock wave associated with this plasma. The hot liquid droplets are oxidized during the process, likely by reaction with atomic oxygen in the breakdown plasma. The roughened surface contains small oxide particles that have been entrained in a rough metal matrix. Increased coupling of 10.6 micron radiation to this surface is believed to be due to this roughening and to the presence of entrained oxide particles.

25 Under heavier processing conditions, i.e. exposure to a greater number of pulses, particle deposition results in the formation of a thick (i.e. less than or equal to 10 microns) oxide layer that yields a high coupling coefficient (i.e. low reflectivity) at 10.6 m. In this case, coupling appears to arise primarily by absorption of incident radiation in this oxide layer.

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5 The above-described surface treatment technique is very rapid and relatively low cost. Moreover, because it is a permanent change in the surface, it is not prone to abrasion and does not change the electrical properties of the surface.

10 When used on an armament, the treatment can be applied selectively to alter the silhouette of the vehicle or to change the signature obtained from the vehicle under laser radar interrogation. Such treatment is effectively a form of electronic camouflage.

15 Similarly, when the surface treatment is applied to a radiating surface such as aluminum, a large number of overlapping pulses produce an almost black oxide coating as noted in Figure 6, providing a very good emitter and therefore enhancing radiative cooling efficiency. This is particularly beneficial on spacecraft where radiative cooling is a dominant effect.

20 With the treatment described above, the overlapping of the pits 18 produces fine grooves on the surface and with repeated scans a bulk surface area of the desired characteristics may be produced. As best
25 seen in Figure 22, a particularly beneficial effect may be obtained if the radiation does not impinge normally to the surface. The axis of the last 10a is inclined to the surface of the material 12a to produce lines 18a as noted above. It has been found that when the laser
30 radiation does not impinge normally on the surface, then the grooves created are undercut or angled with respect to the surface. Such angled grooves produce a change due to both components of reflectivity, that is spectral and diffuse reflectivity, being altered. This again can

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produce a pronounced effect leading to a reduction in the reflectivity of the surface.

5 By processing only selected areas of a surface so as to decrease the reflectivity of these areas, the average reflectivity over a large area can be effectively reduced. This eliminates the need for processing an entire surface so as to reduce its average value to some desired level. For example, in Figure 9
10 selected areas of the surface 14b have been treated as indicated at X. If the reflectivity of the untreated surface is R_A while that of a treated strip is R_X , then the average reflectivity, R , of a sample of total area A containing area X of treated surface is $R = R_X X + R_A (A - X)$. For example, if $A = 1\text{m}^2$, $X = 0.5\text{m}^2$, and $R_A = 0.9$
15 while $R_X = 0.1$; then the average reflectivity of this surface is reduced to $R = 0.5$. This significant reduction in reflectivity has been accomplished by processing only 50% of the surface.

20 The treated areas may be arranged in random patterns across the surface or may follow a predetermined pattern to produce a desired effect. Different areas may be treated in different ways to
25 provide a maximum effect at different wavelengths. Similarly, the treated areas may be applied to selected areas to change the silhouette of a vehicle when interrogated by laser radar.

30 It will be apparent that the surface treatment may be used in a number of ways to provide a change in the reflectivity of a surface. the exact nature of the treatment is variable to produce particularly desirable effects such as a minimum reflectivity to a particular

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wavelength or a black oxide coating to maximize emissivity for black body radiation.

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CLAIMS

1. A method of modifying the reflectivity of a surface of a material comprising the steps of irradiating the surface with a beam of coherent pulsed radiation at a power sufficient to generate a surface plasma and scanning said beam across said surface.

2. A method according to claim 1 including the step of promoting chemical change at said surface.

3. A method according to claim 2 wherein the chemical change is promoted by providing a localised atmosphere at said surface.

4. A method according to claim 3 wherein said localised atmosphere is selected from the group comprising oxygen and nitrogen.

5. A method according to claim 1 wherein said beam scans said surface at a rate to cause successive pulses of radiation to overlap on said surface.

6. A method according to claim 1 wherein said beam is inclined to the surface of the material.

7. A method according to claim 6 wherein said beam scans said surface at a rate to cause successive pulses of radiation to overlap.

8. A method of reducing the average reflectivity of a surface of a material comprising the steps of irradiating said surface with a beam of coherent pulsed radiation at a power sufficient to generate a surface plasma and scanning said beam across selected areas of said surface to reduce the reflectivity of said selected areas, the average reflectivity thereby being reduced as a function of the

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reflectivity and the surface area of the selected areas.

9. A method according to claim 8 wherein said selected areas are arranged in a random pattern on said surface.

5 10. A method according to claim 8 including the step of promoting chemical change at said surface.

11. A method according to claim 10 wherein the chemical change is promoted by providing a localised atmosphere at said surface.

10 12. A method according to claim 11 wherein said localised atmosphere is selected from the group comprising oxygen and nitrogen.

15 13. A method according to claim 8 wherein said beam scans said surface at a rate to cause successive pulses of radiation to overlap on said surface.

14. A method according to claim 8 wherein said beam is inclined to the surface of the material.

20 15. A method according to claim 14 wherein said beam scans said surface at a rate to cause successive pulses of radiation to overlap.

25 16. A method of changing the signature of a surface when interrogated by laser radiation comprising the steps of treating selected areas of said surface to reduce the reflectivity of said selected areas.

30 17. A method according to claim 16 wherein the reflectivity of said selected areas is reduced by irradiating the surface with a beam of coherent pulsed radiation at a power sufficient to generate a surface plasma and scanning said beam across said selected

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areas.

18. A method according to claim 17 wherein said selected areas are arranged to alter the silhouette of said surface.

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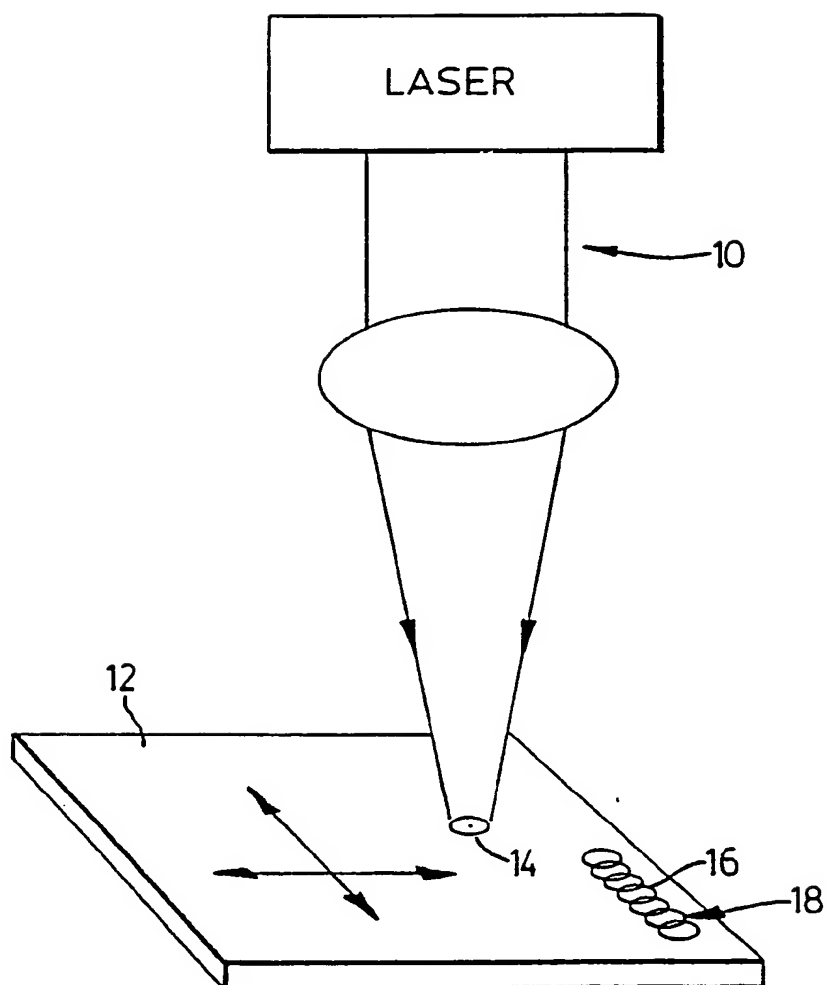
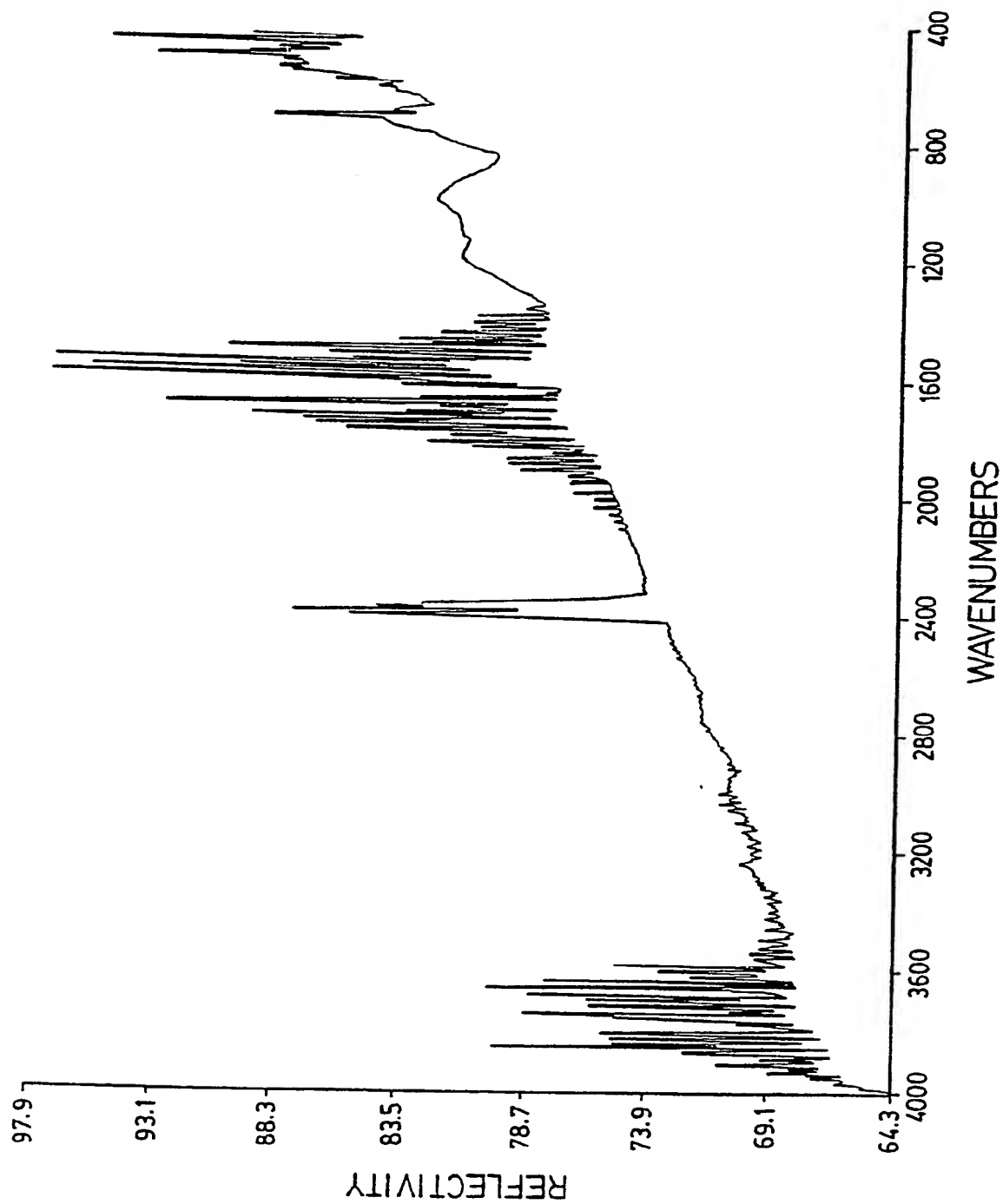


FIG.1

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FIG. 2

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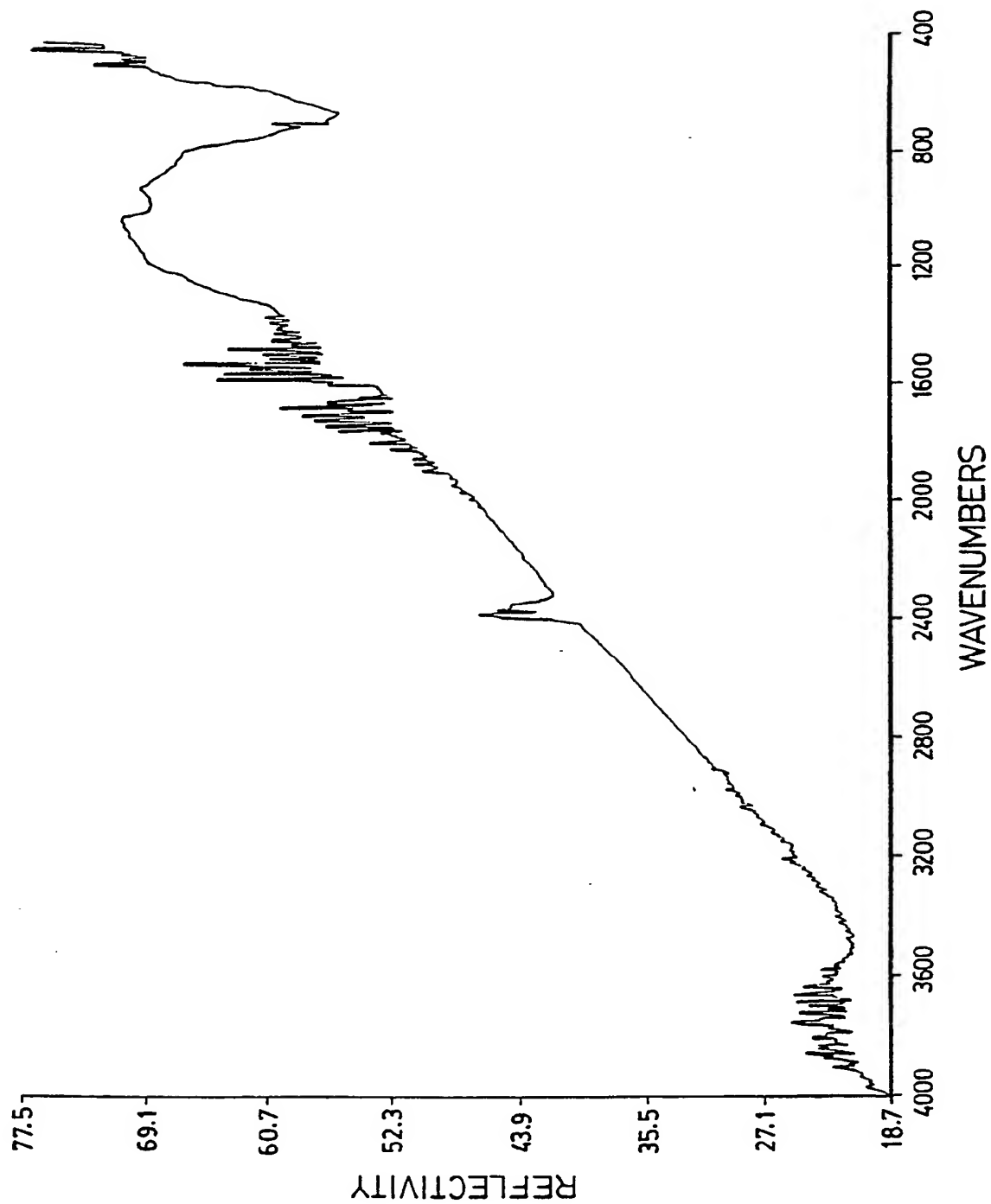
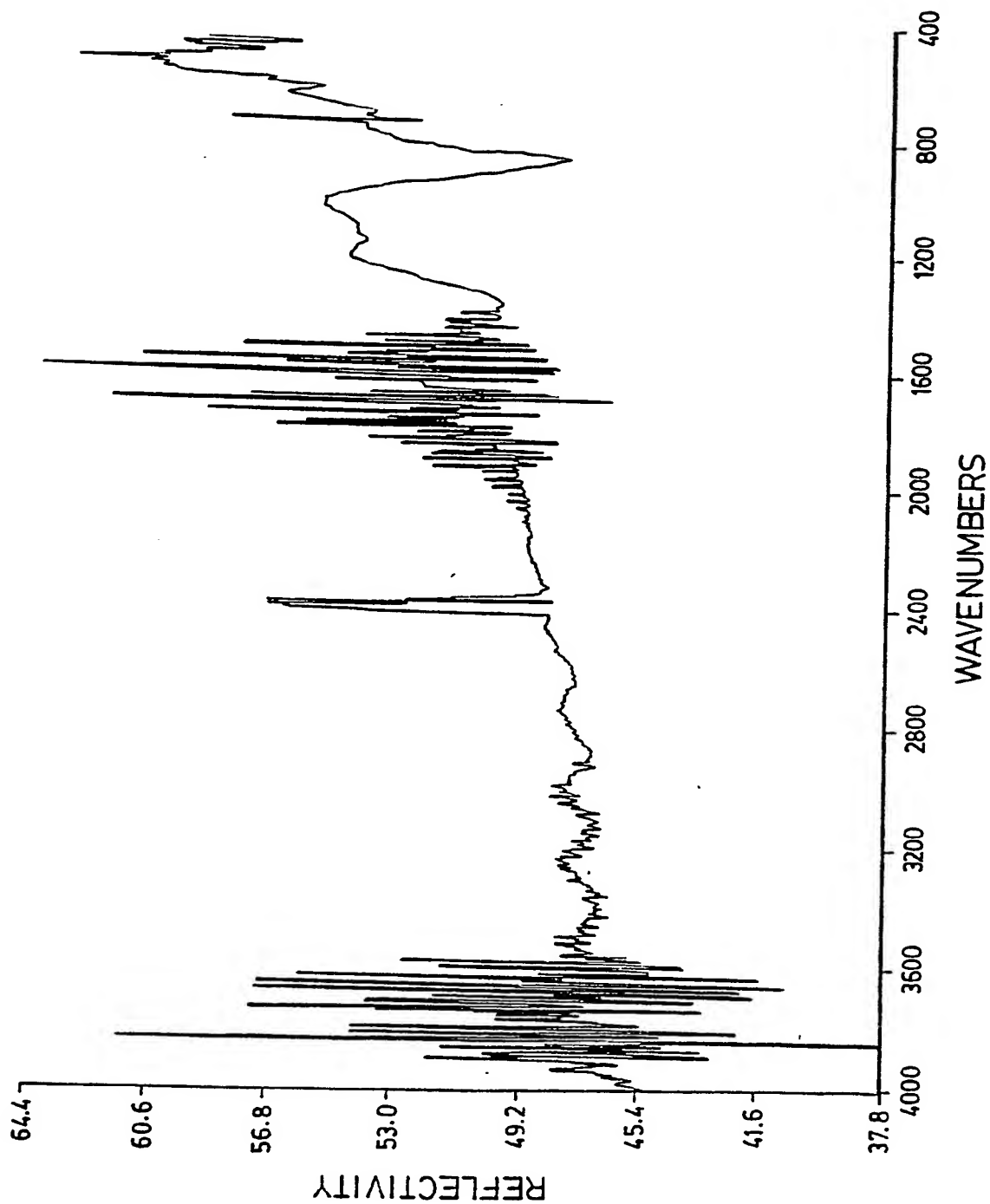


FIG. 3

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FIG. 4

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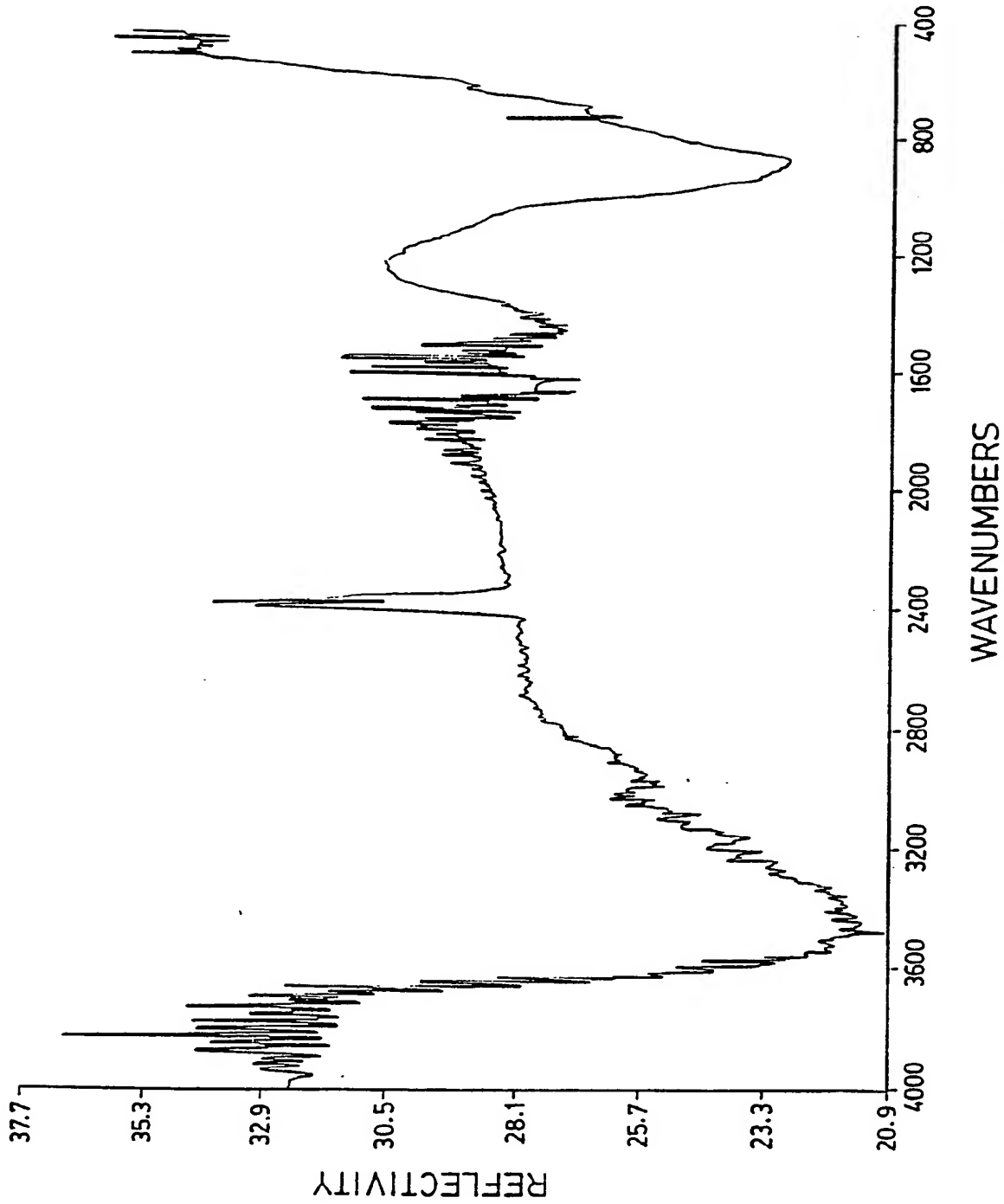


FIG. 5

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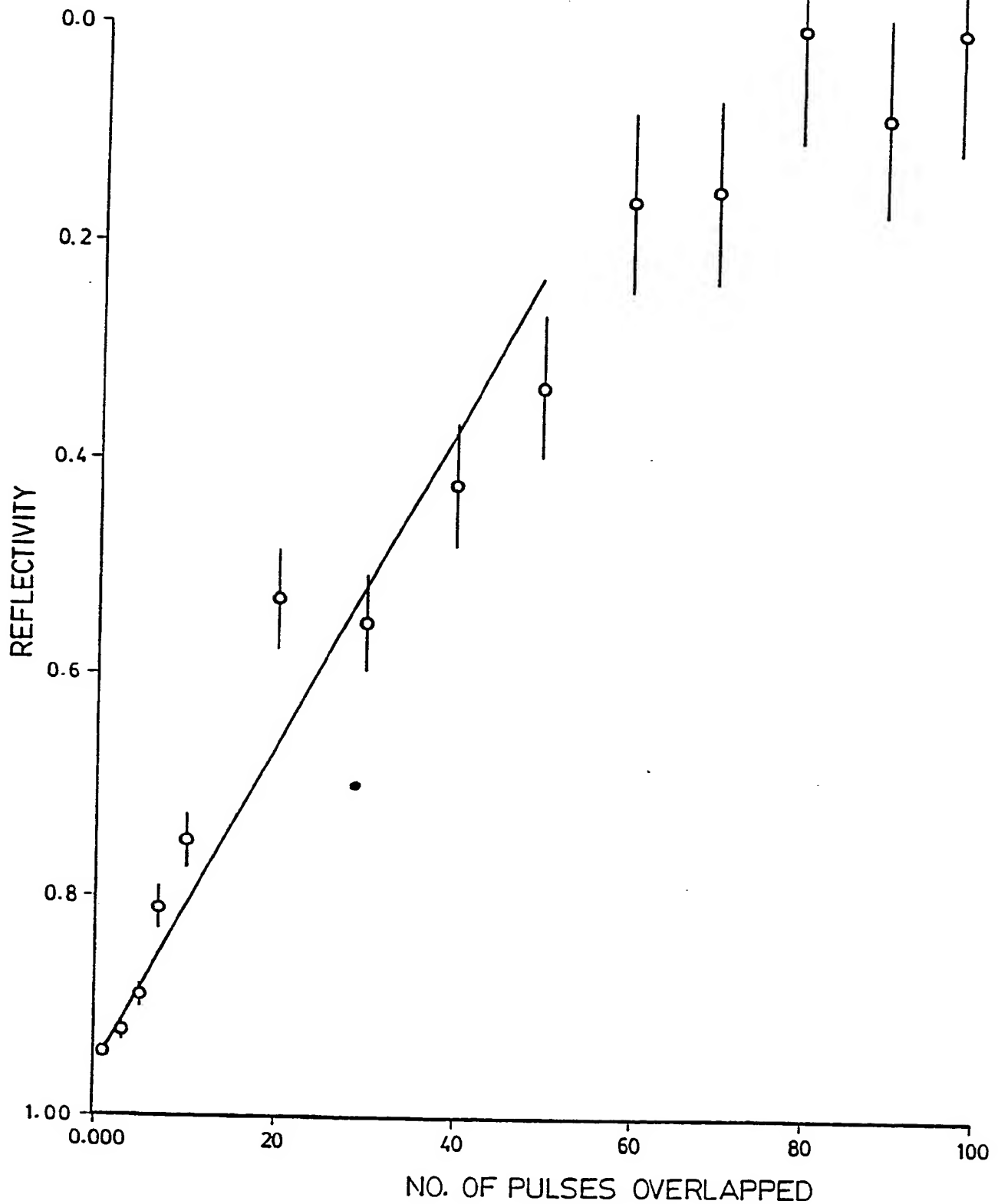


FIG. 6

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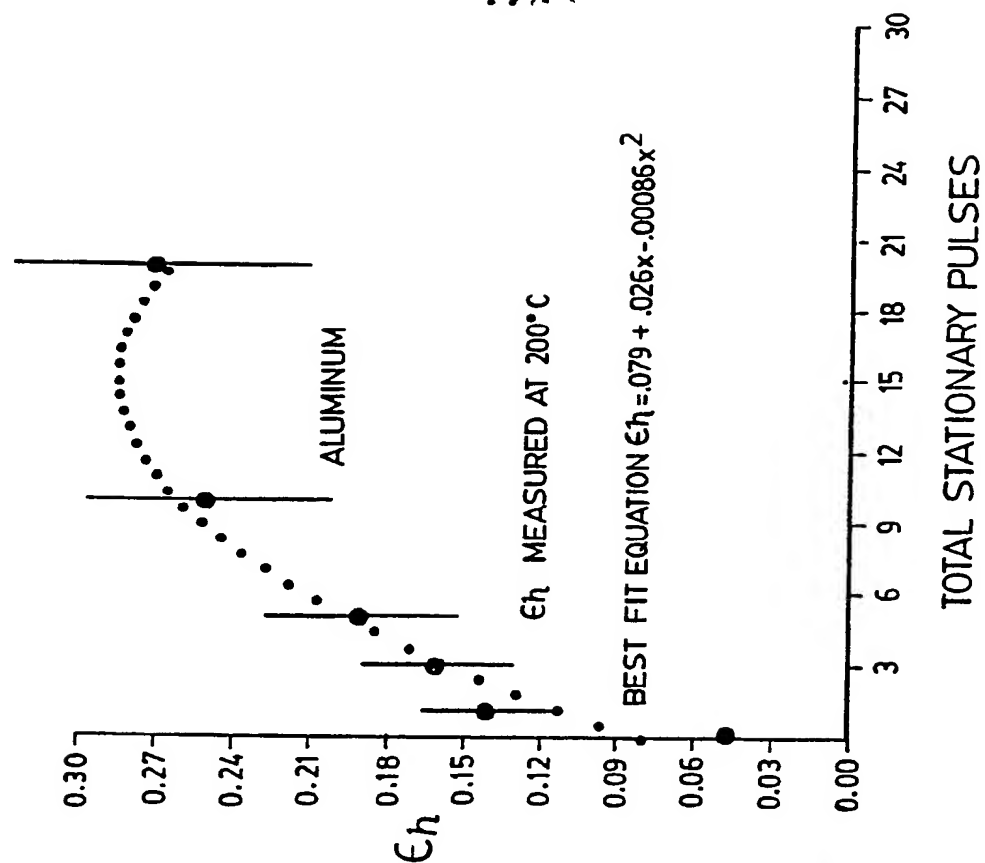


FIG. 8

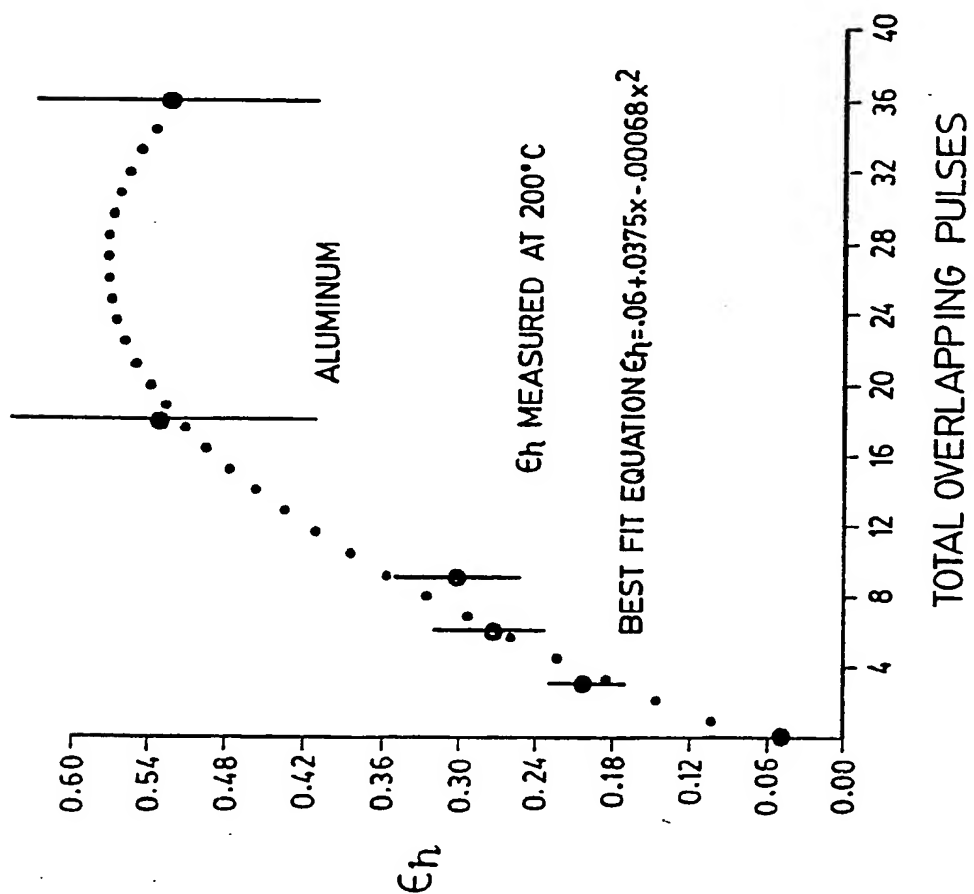
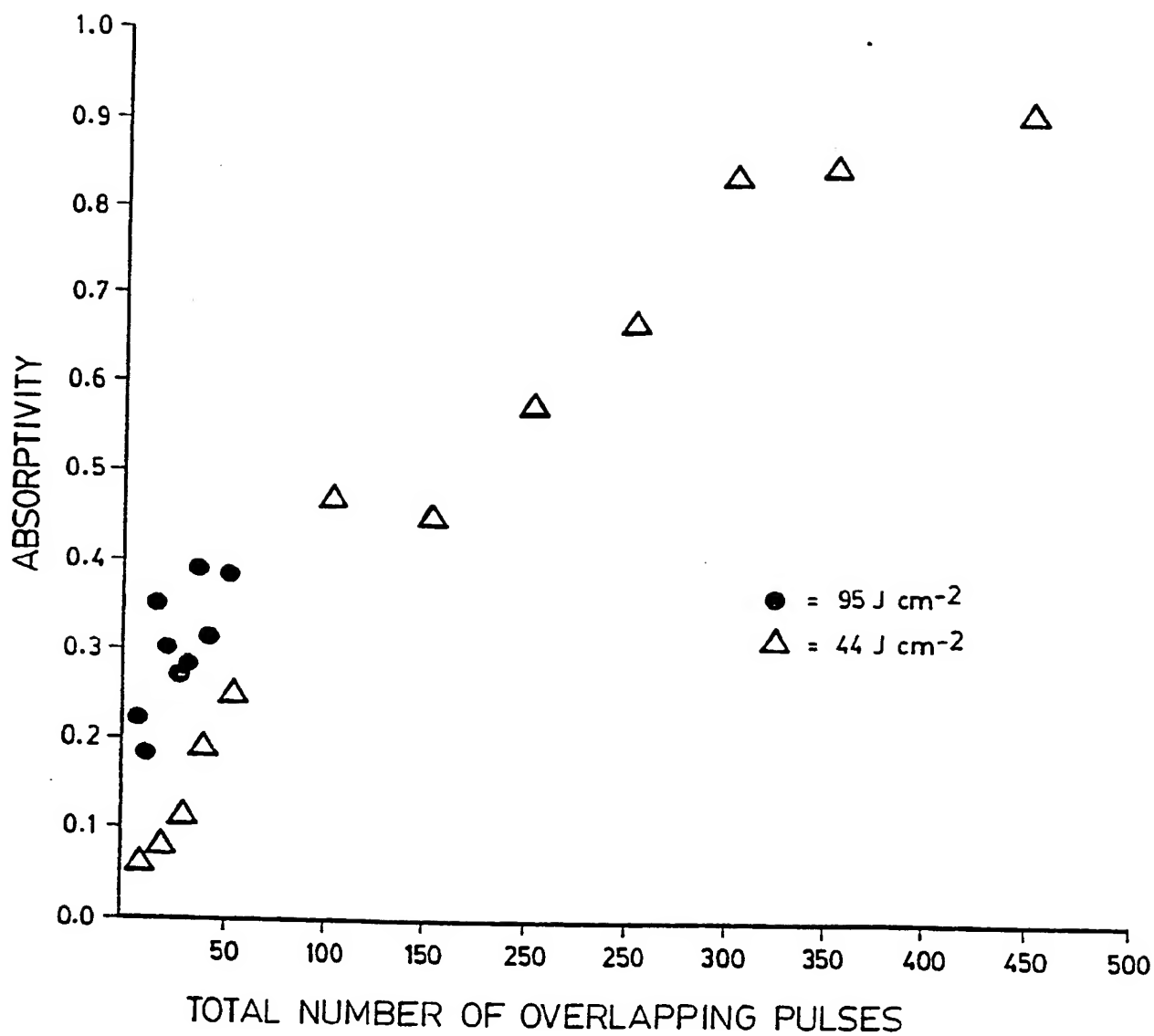


FIG. 7

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FIG. 9

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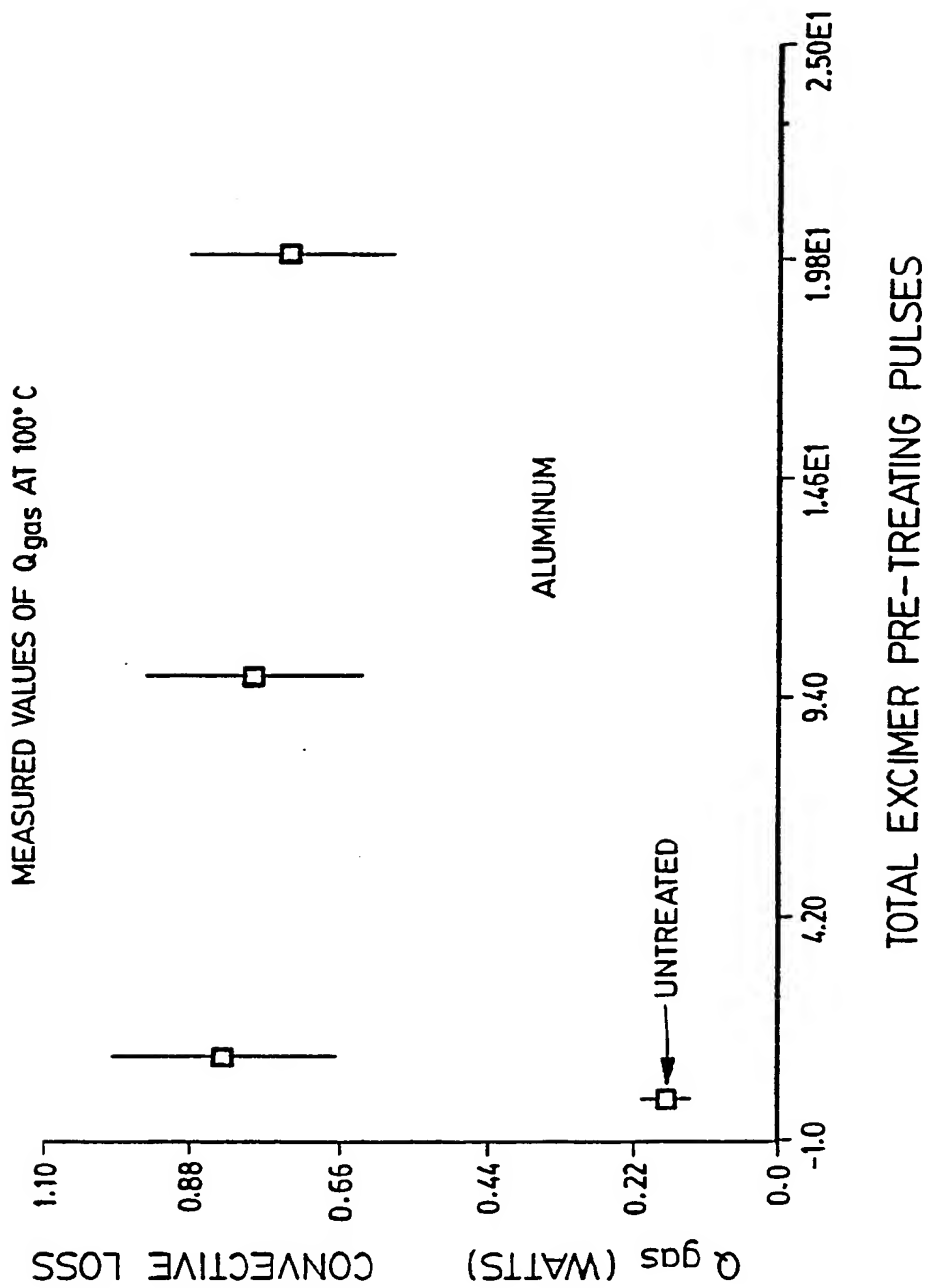
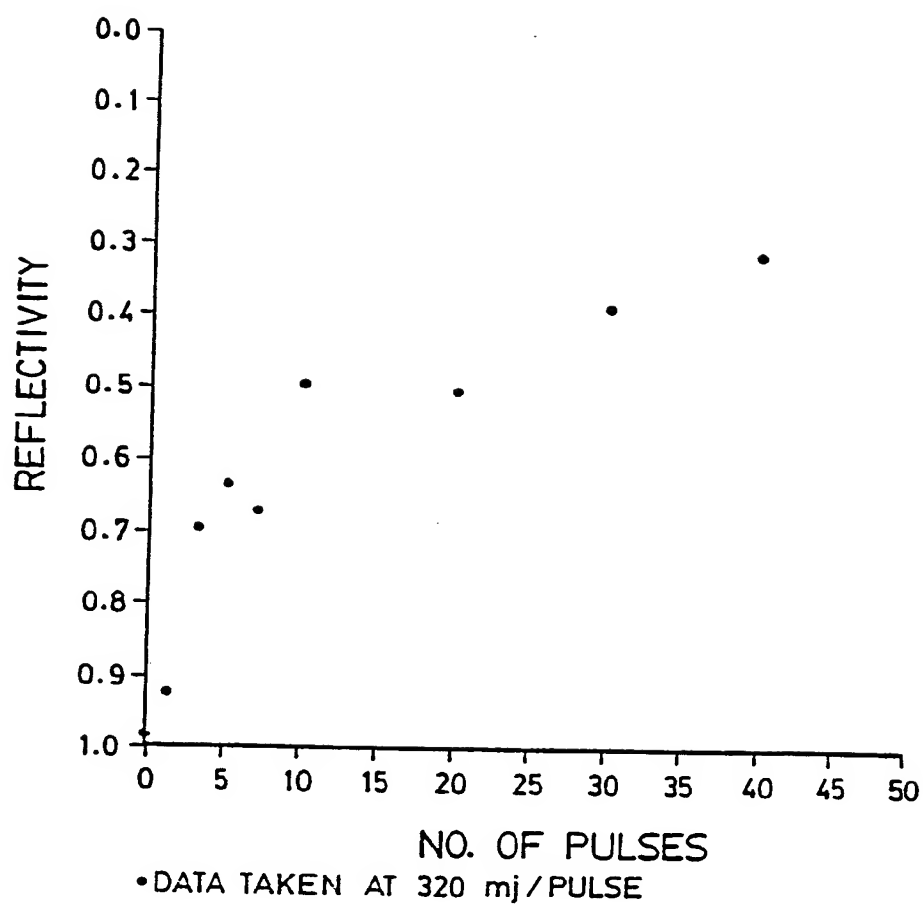


FIG. 10

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FIG. 11

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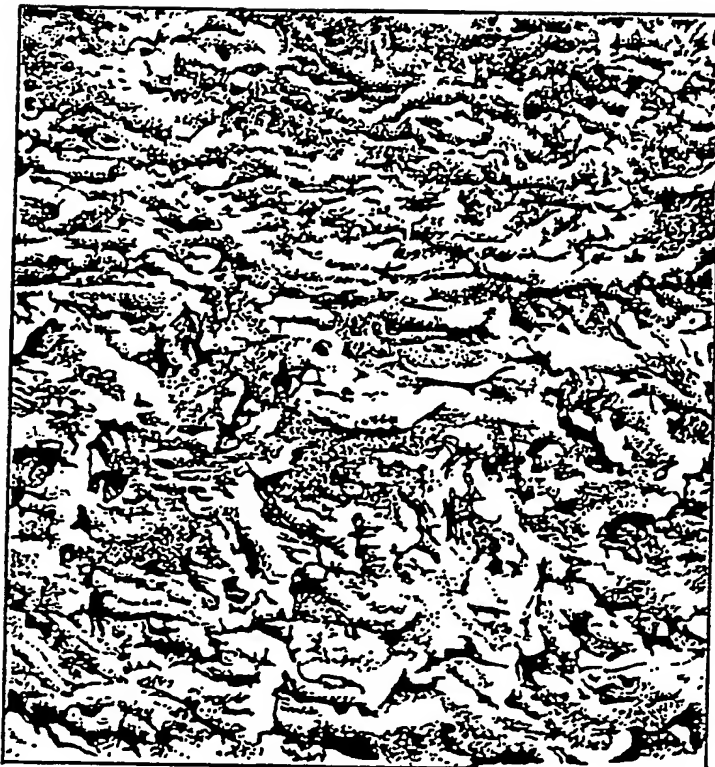


FIG. 12



FIG. 13

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FIG. 14

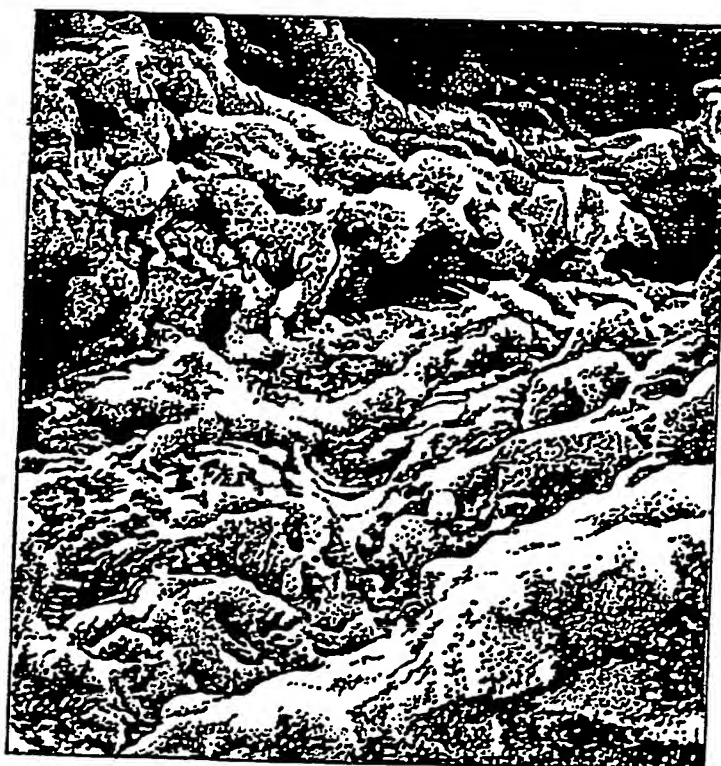


FIG. 15

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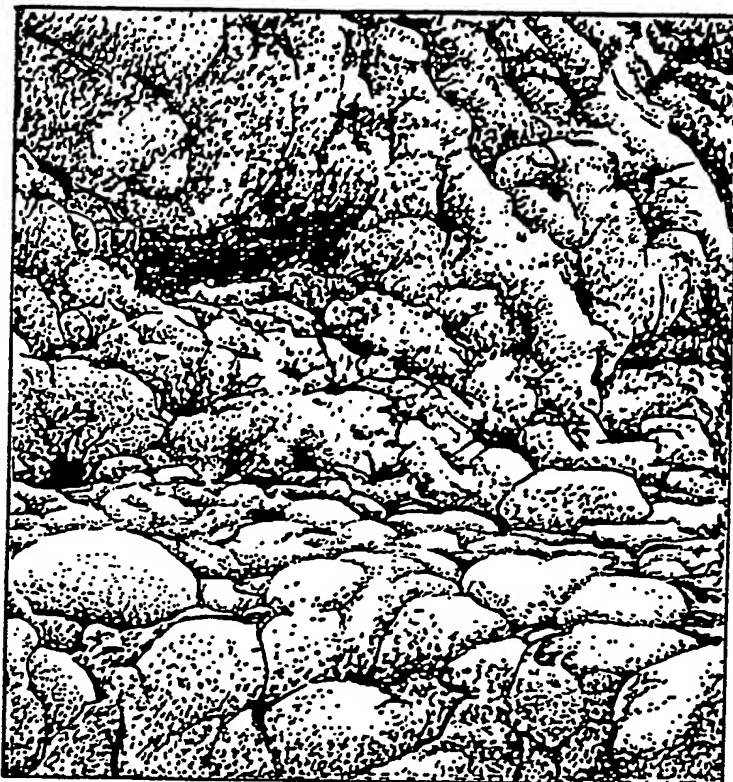


FIG. 16

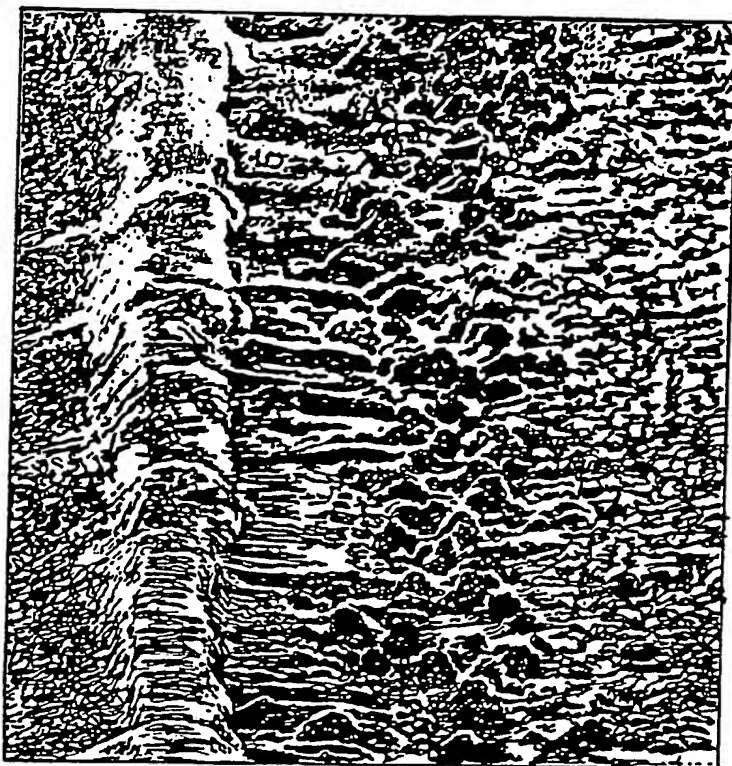


FIG. 17
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FIG. 18

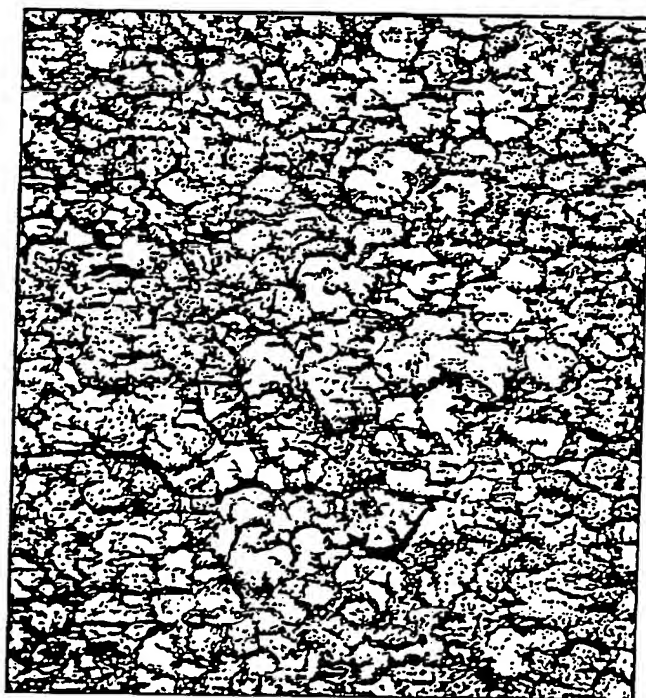


FIG. 19

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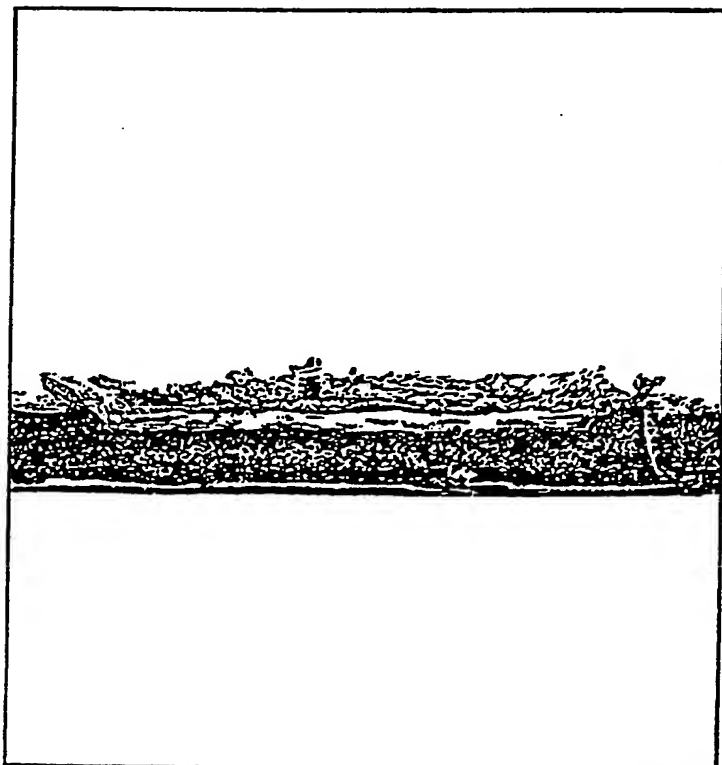


FIG. 20

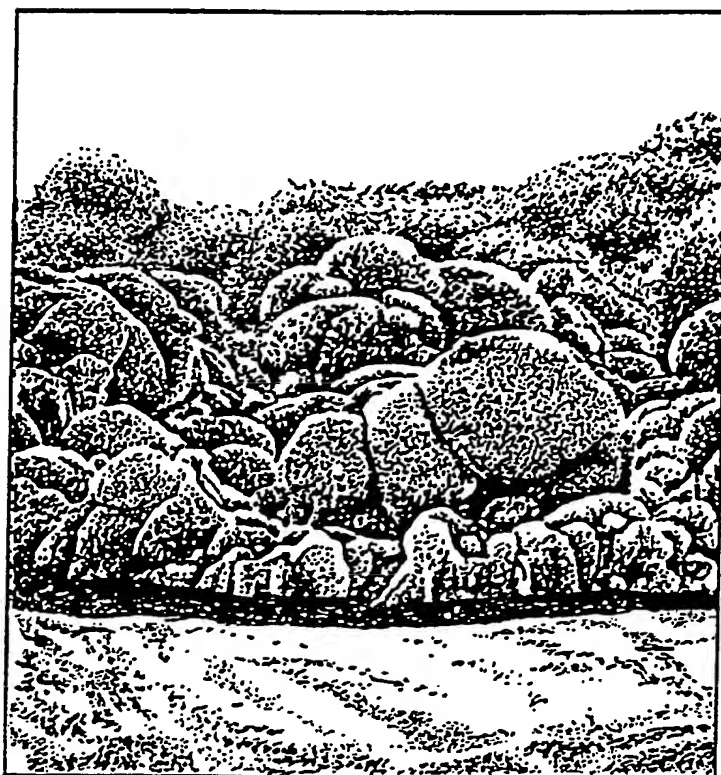


FIG. 21

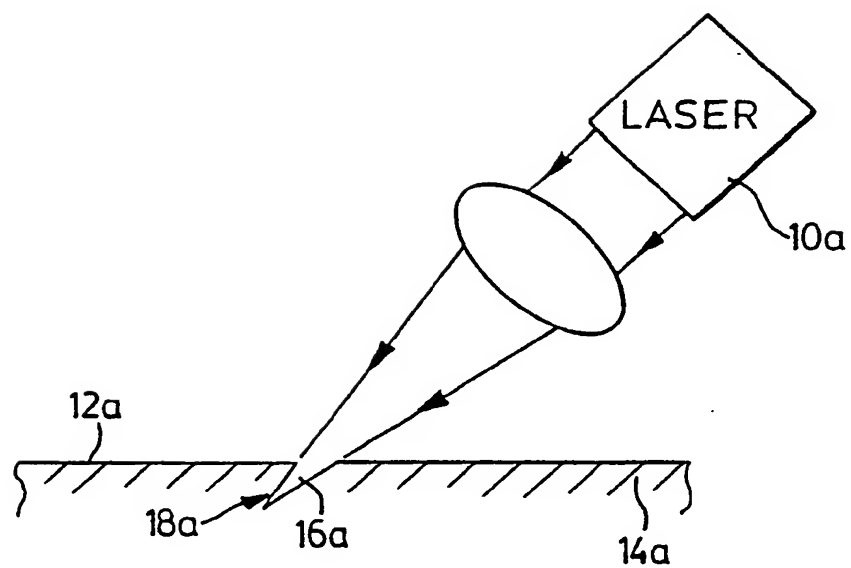
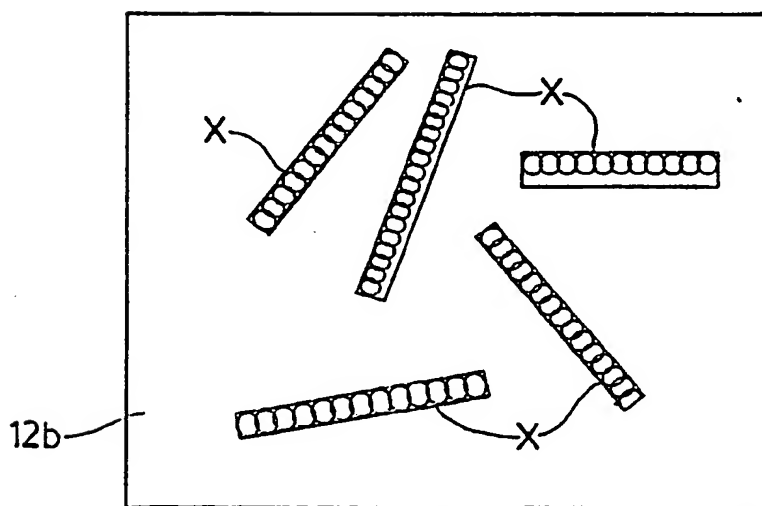
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FIG. 22

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FIG. 23FIG. 24

INTERNATIONAL SEARCH REPORT

International Application No. PCT/US88/04537

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC (4): B23K 26/00

U.S. : 219/121.68, 121.69, 121.6, 121.85

II. FIELDS SEARCHED

Minimum Documentation Searched ⁷

Classification System	Classification Symbols
U.S.	219/121.68 121.69, 121.6, 121.85

Documentation Searched other than Minimum Documentation
to the Extent that such Documents are Included in the Fields Searched ⁸

III. DOCUMENTS CONSIDERED TO BE RELEVANT ⁹

Category [*]	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
Y	US A, 4,500,771 (MILLER) 19 February 1985 See Entire Document.	1,2,5-8,10,13, 14,16-18
Y	US A, 4,547,649 (BUTT et al) 15 October 1985 See Entire Document.	1,2,6,8-10,14, 16-18
X	US A, 4,377,735 (MINA MIDA, et al) 22 March 1983 See Col. 4, lines 24-39	1-18
X	US A, 3,663,793 (PETRO, et al) 16 May 1972 See entire document.	1-18
X	US A, 3,700,850 (LUMLEY, et al) 24 October 1972 See entire document.	1-18
X	US A, 4,028,523 (ANDERL, et al) 07 June 1977 See entire document.	1-18

^{*} Special categories of cited documents: ¹⁰

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search

27 April 1989

Date of Mailing of this International Search Report

18 MAY 1989

International Searching Authority

ISA/US

Signature of Authorized Officer

C.L. Albritton
C.L. Albritton

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

X	US: A, 4,087,672 (Yi) 2 May 1978 See entire document.	1-18
X	US: A, 4,377,736 (DAUNT, et al) 22 March 1983 See Entire document.	1-18
X	US: A, A 4,535,218 (KRAUSE, et al) August 1985 See entire document	1-18

V. ☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE ¹

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1. ☐ Claim numbers _____, because they relate to subject matter ¹² not required to be searched by this Authority, namely:

2. ☐ Claim numbers _____, because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out ¹³, specifically:

3. ☐ Claim numbers _____, because they are dependent claims not drafted in accordance with the second and third sentences of PCT Rule 6.4(a).

VI. ☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING ²

This International Searching Authority found multiple inventions in this international application as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4. ☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

- ☐ The additional search fees were accompanied by applicant's protest.
☐ No protest accompanied the payment of additional search fees.

